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Sequential combination of micro-milling and laser structuring for manufacturing of complex micro-fluidic structures

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Abstract

This paper deals with the combination of micro milling and laser micro structuring for processing hot embossing dies for micro-fluidic applications. This strategy permits the advantages of each process technology to be exploited in order to achieve a cost and time efficient process and also to process forms and structures which cannot be manufactured with the single processes micro milling and laser micro structuring. Basic requirements are a high-precision positioning of the single process areas and also a good machining of the parts and structures with the manufacturing processes micro milling and laser micro structuring. The intersections between the different processing areas present a challenge for this process technology.

Keywords: laser; milling; sequential combination; micro-fluidic; micro manufacturing

1. Motivation

Miniaturization became one of the most important keywords for production technologies in the last years. Whether in microelectronics, medical engineering or production engineering, in all fields, parts and assemblies becoming smaller for a higher functionality in the same space or smaller. In the field of micro production technology, this means an adaptation of established production technologies for the generation of small devices, structures and also the development of new technologies based upon ablation processes. [1]

The department for precision technology and micro-manufacturing of the Fraunhofer Institute for Machine Tools and Forming Technology IWU in Chemnitz deals with the implementation of these processes particularly with regard to manufacturing-oriented process design in the fields of automotive, medical and production engineering.

A distinctive application example for the use of different micro manufacturing processes is micro fluidics, which is important for the employment of medical sensors, for instance. On the one hand, the goal is to produce micro fluidic structures in a range of less than ten micrometers and with a processing accuracy of around one to two microns (see table 1). On the other hand it is necessary to produce these micro structures in a high number of pieces. Hot embossing enables a fast and economic replication of these micro fluidic elements with the requested structural sizes. In hot embossing process, a master structure on a mould surface is pressed into a substrate at elevated

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temperature, forming a negative relief replica of the master topography [2]. Thereby quite different materials like plastics, metal and glass can be structured with a high reliability.

Table 1. Geometrical demands on the micro fluidic structures to be generated [3]

	micro fluidic structure	functional structure
maximal lateral dimensions	50 mm	750 µm
minimal lateral dimensions	25 µm	5 µm
maximal structure depth	500 µm	20 µm
maximal aspect ratio	5	15
dimensional accuracy of components	± 1 µm	± 1 µm
position accuracy	± 5 µm	± 5 µm
surface quality	Rz < 500 nm	Rz < 500 nm

The manufacture of the hot embossing tool, is a key element in any hot embossing operation conducted on microstructures. Firstly, this tool must feature the female mould of the structures required and secondly, it has to resist the developing process forces and very high process temperatures (in excess of 750 °C).Therefore only highly heat resisting high-alloy steels and ceramics are suitable. Normally, the structuring is done by milling or thermal ablation methods. This fact implies restrictions relating to the material and the producible structural sizes. The established process technologies reach their limits because of its technological and also physical properties in the field of micro production technology. These properties are defined by the requirements of micro parts like required structural sizes, forms and also by the used materials. To resolve these limits on the one hand new production technologies like laser ablation or electro chemical manufacturing can be used. And on the other hand, the combination of new and established production technologies brings an interesting starting point to overcome the existing technological limits.

2. State of the Art

2.1. Micro milling

Milling methods enable first of all the machining of metallic materials. In the field of micro manufacturing, the milling technology is typically used for the machining of tools, dies and prototypes (see figure 1). Although milling tools with diameters down to 50 microns can be used reasonable under conventional manufacturing conditions.

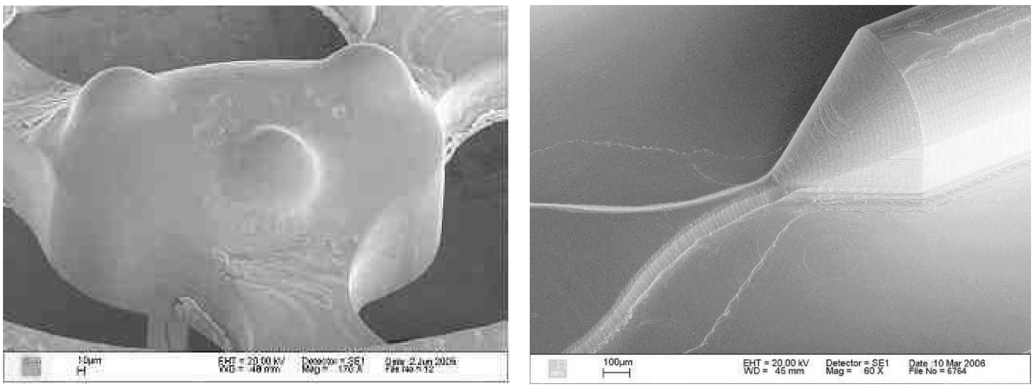

Figure 1. (a) Implant of ear section (titanium); (b) Detail of a hot-embossing tool with a female mould of a micro fluidic structure

There are restrictions in relation to the structure shapes and sizes which can be achieved. The minimum tool diameter limits the sizes of channels and the forming of an inside radius (see figure 2). Other restricting factors are the achievable aspect ratio, the low chip volume and the comparatively high processing time while using a very small micro milling tool.

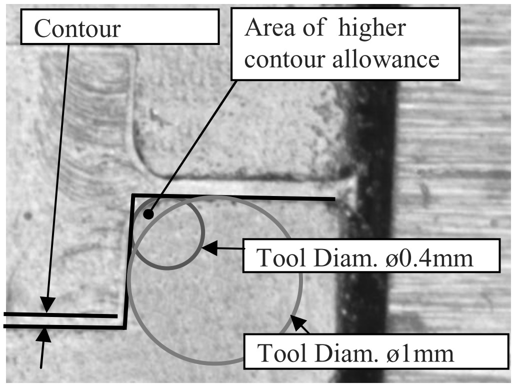

Figure 2. Machinable structural sizes in relation to the tool diameter [4]

Basically it could be said the smaller the tool diameter the better is the machinable structural fineness. Concurrently the machinable chip volume is decreasing. This can be compensated during processing by using different tool diameters. This permits to machine larger areas with larger tools to reach a higher chip volume. Small tool diameters are used only for fine structuring operations. But the multiple tool changing contains the risk of imprecision and machining errors because of the existing tool tolerances and the repeated detecting of the zero point in the z-direction at the surface of the workpiece. Furthermore the minimal reproducible structural sizes and theaspect ratios are limited by the available tool sizes.

2.2. Laser machining

Alternatively laser machining can be used for micro structuring instead of micro milling. The well feasibility focussing of the laser beam and a high energy density enable the manufacturing of different structural shapes and sizes as well as the machining of a wide range of materials (see figure 3).

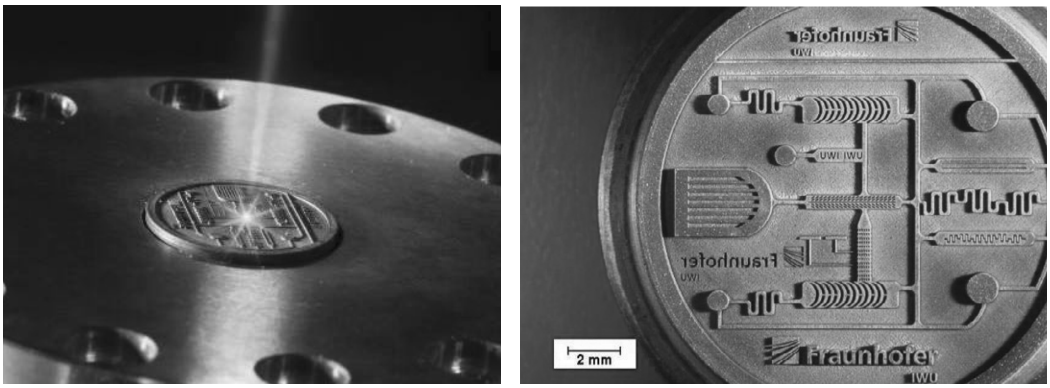

Figure. 3. (a) Laser machining of an embossing die; (b) Embossing die with micro fluidic structures (silicon carbide)

Laser technology has been qualified as a micro structuring technology because it is characterized by high power density on a small spot area, the applicability to a wide variety of manufacturing processes and its suitability for machining difficult to machine materials like ceramics, carbide and hardened steel with excellent productivity and surface quality [5, 6]. Laser ablation shows clear advantages in comparison to traditional milling or electro discharge machining like the nearly unlimited choice of materials, direct usage of CAD structure data, high geometric flexibility and a non-contact machining [7, 8].

The very small size of the laser spot diameter (tool diameter) is on the one hand a great advantage in the production of very small structural elements. On the other hand this fact is a disadvantage concerning the suitable ablation rates over a complete workpiece or operating range. The small diameter of the laser spot requires a large number of laser paths to produce a defined structure over a prescribed area. This means the larger the machined area, the higher increases the processing time. The material ablation takes place in several processing layers until the final structure or contour is produced (2.5D-processing). To get a high structural accuracy it is necessary to reduce the deepness of laser ablation. This raises again the ablation rate in larger areas.

2.3. Comparison of advantages and disadvantages of both machining technologies

A comparison of laser ablation and micro milling techniques reveals that both methods are generally dedicated to processing minimal structural geometries, e.g. typical tool structures for micro fluidics. However there are specific restrictions concerning the structure sizes and shapes which can be achieved, as well as the feasible ablation rates (see figure 4).

process	pro	contra
micro milling	high material removal rate	limited miniaturizability (structural sizes >> 0.01 mm)
micro laser ablation	excelent miniaturizability (structural sizes < 0.01 mm)	low material removal rate

combination of micro milling and micro laser ablation

Figure 4. Advantages and disadvantages of compared machining technologies

A meaningful approach for using the advantages of both methods is the process combination of micro-milling and laser ablation. For very small geometrical elements and structural sizes with dimensions of a few microns up to dimensions around a few hundred micrometers, the laser ablation is the preferred machining technology. For larger structures and areas, the micro milling can be used to reduce the processing time through higher ablation rates.

3. Problem analysis / method of solution

A fundamental problem in machining micro fluidic tool geometries is machinability of the required structures. The goal is the complete machining of the structures with the best geometrical accuracy. As shown in the previous section, the used micro technologies offer specific process limits, which make the machining of special geometrical elements, structural sizes or materials complicated or impossible.

Therefore, geometrical forms und sizes can’t be manufactured with the respective single process technology. The main subject of current research is the supporting combination of processes. An example for this is the laser assisted milling, in which the basic material is heated by laser to realise a better machinability by milling [9]. In the present paper the sequential combination of the processes laser micro structuring and micro-milling will be explored. This process was investigated with an example of micro fluidic structures for embossing dies. The required process parameters are selected based upon existing experiences in the work with the individual process technologies to realise a highly precise manufacturing by the combination of these two processes. For first experiments a tempered high-grade steel (X3CrNiMo13-4) was selected chosen. On the one hand, it is a typical material for injection moulding and hot embossing tools and on the other hand it has a good machinability for laser machining and milling.

For these investigations two separate test stands for laser structuring and micro milling were prepared and used. The experiments on micro milling, took place on a special test facility for high precision milling. This test facility was developed together with LPKF Motion & Control [10]. The innovative motion concept based on voice coil principle in combination with high sensitive measuring scales by Heidenhain enables micro milling processes with highest precision with an absolute accuracy less than one micron. For laser structuring a special test stand with a frequency doubled Nd:YAG laser and with a specific scanner unit was used. The workpiece clamping was realized on both machining systems by a highest precision zero-point clamping system EROWA-FTS which was developed especially for micro manufacturing. The position alignment of milling and laser machining fields to each other was supported by external optical measuring equipment.

4. Sequential processing of laser machining and micro milling

4.1. Test geometry

Based on established microfluidic structures a test geometry (see figure 5) with different elements was defined. The aim was to simulate critical domains for the micro manufacturing. The whole structure has a size of 10.5 mm x 6.5 mm.

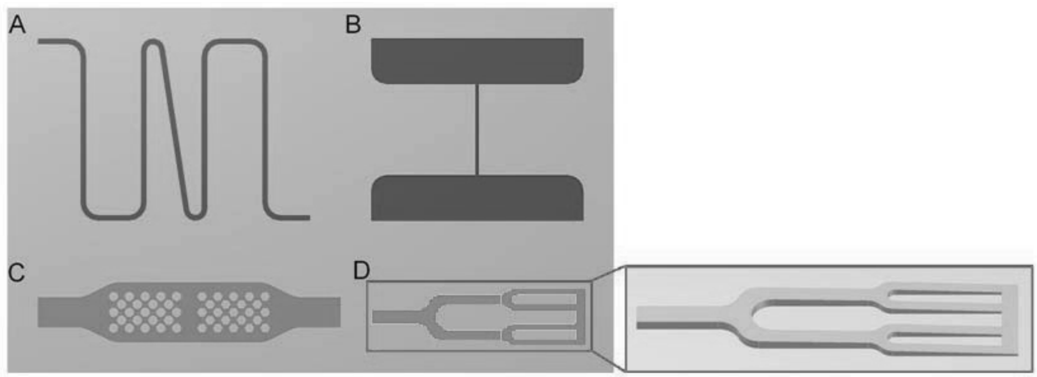

Figure 5. General view of test geometry

Based upon the elements A – D different conditions for the manufacturing shall be simulated. Element A shows a meander structure which can be used as a micro fluidic channel. Difficult to machine at these structure are the radii and the distances between the bars. Structure B can be manufactured by milling although the small bar. The problem for manufacturing is the right angle between bar and basic structure which can’t be manufactured with a end mill cutter. Structure C illustrates a measuring chamber with different slots for a micro fluidic system. The slots have a diameter of 0.15 mm. That’s why it is difficult to machine it with the used milling tools. The fourth element (structure D) shows a branched bar structure with a slant surface. Such structures are often used as a hopper in the fluidic system. The gaps between the bars are at minimum 0.15 mm.

4.2. Processing limits of the used single processes

The first step was the machining of the whole geometry by the single process technologies. Thereby the limits of the technologies can be marked and the required processing times could be detected. To normalize the tests and to ensure a direct comparison between laser and milling process, no tool change is carried out. In each case only one tool diameter is used (for milling) in the machining process.

A tool with a diameter of 0.3 mm was used to establish the limits for the milling process in terms of minimum structure sizes. The test showed that not all parts of the test structure can be machined due to small structure gaps and that internal corners arise, which cannot be manufactured using the tool diameters in question. A simulation (dry run) with an end mill cutter Ø 0.1 mm was performed in order to identify the processing time required for milling. The test showed that not all parts of the test structure can be worked on in regard to small structure gaps and internal corners arise which can’t be manufactured with the used tool diameters. To identify the processing time for milling a simulation (dry run) with an end mill cutter Ø 0.1 mm was carried out. The tests showed a processing time (only milling) of approx. 340 minutes for the structure.

In comparison the whole structure was manufactured by laser ablation (see Figure 6). This showed that the machining of al requested structures is possible. Due to the small focal point of the laser beam (tool diameter) the processing time for laser ablation of the whole structure amounts approx. 330 minutes.

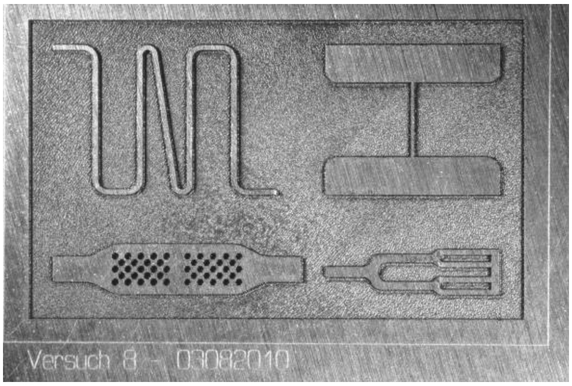

Figure 6. Machining of the whole geometry by laser ablation

4.3. Alignment of the single references in regard to the used machines

A sequential processing of laser and milling can be realized by to different ways. On the one hand combined processing centres with various technologies in one arrangement are described in different research reports [11, 12]. Although this solution has the advantage of avoiding difficult positioning for each processing step, it also has a disadvantage that each technological process is taking place in a single mode. So the economic efficiency of manufacturing cannot be improved in an essential way. On the other hand it is possible to use two different machines for the sequential laser and milling process. The challenge at this is the high precision orientation of the single references (angular position, orientation and scaling). Additional measuring equipment is required to calibrate the manufactured structures for the subsequent steps.

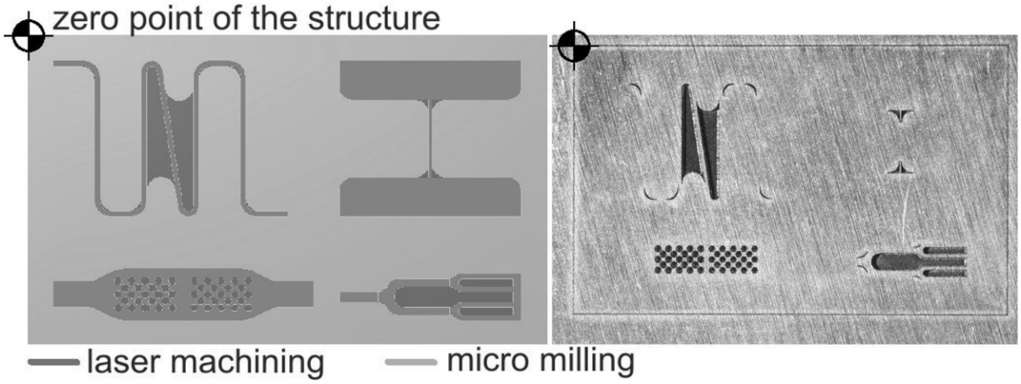

Figure 7. Zero point detection for laser machining and micro milling

In the present work the used processing systems could be calibrated by the use of special test geometries. The adjustment is taking place by identified correction values.

The first process step is the laser ablation (see Figure 7) whereby the first structures are processed. The subsequently adjustment of the milling structures occurs with the help of a zero point detection and the detection of the offset in regard to the laser structure.

4.4. Tests with the sequential laser and milling process

The milling program for the structure was generated for three cutter diameters (0.3 mm, 0.5 mm und 0.8 mm). In Figure 8 the segmentation of the three resulting programs are shown. The green areas define the desired (fluid) structure and the grey areas show the parts which can be manufactured with the respective cutter diameter. The resulting red fields have to be structured by laser ablation. Between laser and milling a domain an overlap of approx. 50 microns is included.

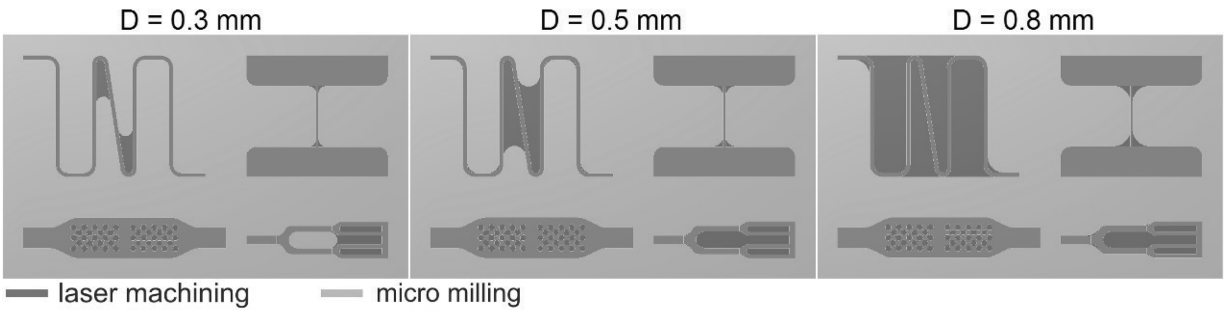

Figure 8. Laser and milling areas in regard to the used milling tool

The experiments to combine the processes of micro-milling and laser structuring had been token place on two separate, independent machines. It was, therefore vital to ensure sufficiently accurate and repeatable positioning in the working space between the micro-milling cutter / focused laser beam and the tool geometry to be manufactured.Consequently, the extremely high accuracy requirements relating to the precision clamping systems and any additional optical sensors and camera systems are extremely high [13].

The chosen process sequence for the tests is a laser ablation with subsequent milling process. What ensure a good crossing between the worked on areas. By milling a defined depth can be reached (infeed depth by a z-axis) and so it is possible to refinish the worked on surfaces by laser ablation.

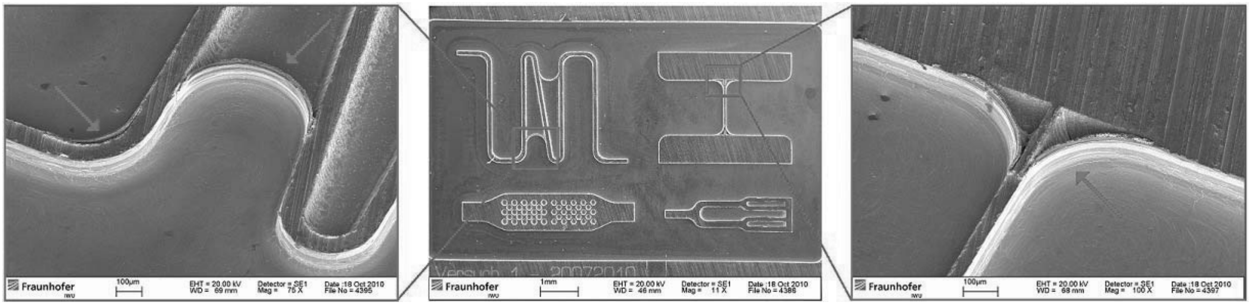

Figure 9. (a) Crossover section between laser (above) and milling area; (b) Test structure; (c) An unrequested bar between milling and laser area

In fig. 9(a-c) typical errors scheme from the beginning of the experimental work are shown. At first the combination of milling and laser structuring causes a different surface quality. A further problem represents the unavoidable crossover sections (see the marking in fig. 9a and fig. 9c) between the various processing areas for milling and laser. Also short residual positioning errors of the working fields inside the two separate working spaces of the machines are abounded.

Through the further optimization of the described positioning algorithm on each machine system the failure rate could be reduced extensively (see figure 10). Reducing the laser ablation down to the geometrical forceful level it succeeds an essential decrement of the over-all processing time.

5. Results and Discussion

The investigations have shown that a combination of different manufacturing processes, especially in the field of micro manufacturing, enables to generate selective micro structures with very high geometrical accuracy and in an excellent quality. In doing so it is possible to achieve shorter processing times as with the particular single manufacturing method (see fig. 10a). Finding an effective and reproducible method for precise positioning of the workpieces or rather the pre-processed micro structures in the working space is essential to realize the required high-precision adjustment between the micro tool (cutter or laser beam) and the workpiece geometry.

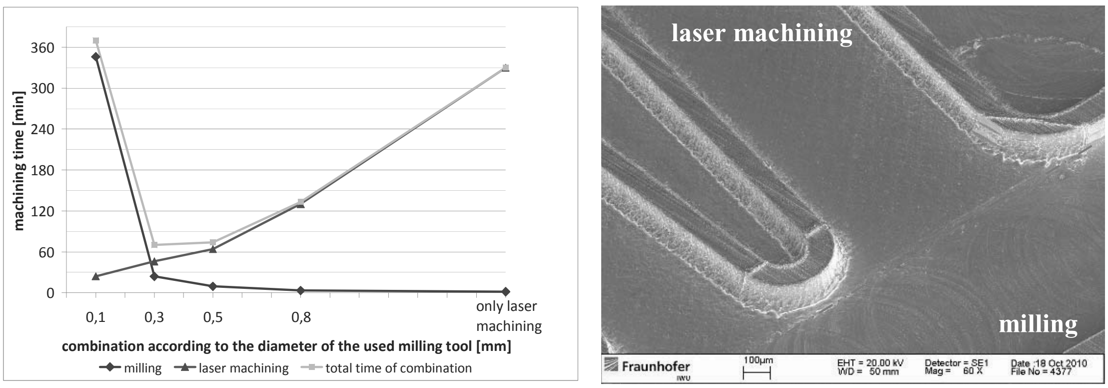

Figure 10. (a) Processing time of the micro fluidic test geometry; (b) Sample of a well done combination of laser structuring and milling with D=0,8mm (compare with Fig. 8)

The used technologies have to be harmonized with highest accuracy to enable a controlled material abrasion of the discrete processing areas without distracting ledges in the ground or at geometrical flanks. In the same way the tuning of the size of roughness has to be improved over the different processing areas so that a good material removal and concurrently a high surface quality can be achieved over the whole geometrical structure.

By means of the experimental work using the example of micro fluidic tool geometry it could be shown that a combination of laser structuring and milling to manufacture ambitious micro structures is suitable and reasonable.

By selective exploitation of the specific advantages of the single technologies laser structuring and milling on the one hand it was possible to conquer technological limits of micro milling, e.g. the small size of the structures or a very small flanging radius, and on the other hand the advantages of the micro milling like an excellent surface quality and in opposition to the laser an essential limitation of the processing could be used in a good way.

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